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A one pot one step combined radical and ring-opening route for the dual functionalization of starch in aqueous medium

Julie Meimoun,^a Vincent Wiatz,^b René Saint-Loup,^b Julien Parcq,^b Adéline David,^c Grégory Stoclet,^c Valérie Gaucher,^c Audrey Favrelle-Huret,^a Fanny Bonnet,^c Philippe Zinck^{a*}

^a Univ. Lille, CNRS, Centrale Lille, ENSCL, Univ. Artois, UMR 8181 - UCCS - Unité de Catalyse et Chimie du Solide, F-59000 Lille, France.

^b Roquette Frères, F-62080 Lestrem Cedex, France.

^c Univ. Lille, CNRS UMR 8207 – UMET - Unité Matériaux et Transformations (UMET), F-59000 Lille, France.

Starch based materials are attractive bio-based alternative to fully synthetic polymers. Native starch has however limited thermoprocessability and properties and must be modified. In order to improve the properties of starch-graft-poly(butyl-acrylate-*co*-styrene) copolymers via a process as green as possible, we report herein a new method for the dual functionalization of the polysaccharide via a one pot one step reaction in aqueous medium combining free radical polymerizations and ring-opening chemistry. Poly(butyl acrylate) / poly(butyl acrylate-*co*-styrene) (ca. 60 000 g/mol) and oligo(ϵ -caprolactone) were grafted on starch with a grafting percentage up to 75 %. The copolymers show two glass transition temperatures: one around 55-60°C related to starch and a second attributed to the grafted vinyl polymers, from -46°C to 20°C depending on butyl acrylate/styrene ratio). The resulting dual functionalized materials exhibit excellent mechanical properties, with elongation at break in the range 20-210 %, while single functionalized starch shows less than 5 %.

Keywords: starch, graft copolymerization, structural / thermomechanical properties.

1. Introduction

Research towards biobased and biodegradable polymers has received much attention this last decade, due notably to environmental concerns and the depletion of oil resources (Chen, Kamitakahara & Edgar, 2020; Imre, García, Puglia & Vilaplana, 2019). In this context, starch is a promising starting material due to its availability and low cost that has been the subject of numerous studies (Chen et al., 2015; Fan & Picchioni, 2020). However, starch has limited thermoprocessability along with a strong hydrophilic character and poor mechanical properties as compared to conventional synthetic polymers (Avérous & Halley, 2009). Starch can be plasticized with external plasticizers such as polyols (Lourdin, Coignard, Bizot & Colonna, 1997), urea/formamide combinations (Xiaofei, Jiugao & Jin, 2004) notably. However, some shortcomings, as plasticizer migration, induce an evolution of its properties over time and thus limit its applications.

To overcome some of these drawbacks, the polysaccharide can be blended with synthetic polymers (Wang, Yang & Wang, 2003), functionalized to yield starch esters and ethers (Aburto, Alric & Borredon, 1999; Shogren, 2003) or grafted with a polymer (Meimoun et al., 2018; Cazotti et al., 2020; Haq et al., 2020). Graft copolymerization is a very versatile way of functionalization allowing access to materials displaying a combination of the properties of the synthetic polymer and of the starch (Jyothi,

2010). In particular, the radical graft copolymerization can lead to starch-based materials with interesting properties. In this frame, the synthesis of starch/starch-*graft*-poly(butyl acrylate-*co*-styrene) copolymers by free-radical graft polymerization was conducted on native (Meshram, Patil, Mhaske & Thorat, 2009), acetylated (Mou, Li, Wang, Fei & Liu, 2012) starch and dextrin (David et al., 2019). Starch can also be modified by grafting polyesters on its backbone by ring-opening polymerization (ROP) in organic solvents (Chen et al., 2005; Rutot-Houzé et al., 2004) and in water (Choi, Kim & Park, 1999), a tin based catalyst being used for this purpose.

The combination of the two processes, *i.e.* radical and ring-opening grafting onto polysaccharides can give access to advanced materials with applications such as drug, fragrance containers or stimuli responsive materials (Chang, Yamabuki, Onimura & Oishi, 2008; Liu, Huang, Pang, Han & Ji, 2015; Yan et al., 2009). Diblock copolymers were grafted onto cellulose by combining in a sequential way ROP and Atom Transfer Radical Polymerization (ATRP), involving the use of copper halide, amine ligands and, in the examples reported herein, 2-bromopropionyl bromide (Berthier, Herrmann & Ouali, 2011; Östmark, Nyström & Malmström, 2008). In these studies, polyester is grafted as the first block by ROP of a cyclic ester, eventually after a first protection step of a part of the hydroxyl groups. The polymer chain end is further derivatized to yield an initiator for the controlled radical polymerization of a second monomer, leading to the second block.

The dual functionalization, *i.e.* the grafting of two different oligo/polymers was reported onto cellulose powder and cellulose derivatives such as hydroxyethylcellulose or diacetate cellulose by a multistep procedure involving the grafting of the controlled radical polymerization initiator (Chang, et al., 2008; Liu et al., 2015; Vlček et al., 2008). As a representative example, the radical macroinitiator is formed at the first step by the reaction of hydroxyl groups with 2-bromopropionyl bromide in a mixture of tetrahydrofuran (THF) and trimethylamine. The tin catalyzed ring-opening polymerization of ϵ -caprolactone initiated by the remaining hydroxyl groups is then realized in xylene, followed by the ATRP of *N,N*-dimethylaminoethyl methacrylate in THF in the presence of *N,N,N',N'',N'''*-pentamethyldiethylenetriamine (PMDETA) and CuBr (Yan et al., 2009).

The combination of radical and ROP processes was, as far we know, reported onto cellulose and never onto starch. The synthetic strategies reported in the literature involved multistep procedures, the use of organic solvents (*e.g.* THF, xylene), harmful compounds for the initiation of the controlled radical polymerization (*e.g.* copper halide, brominated derivatives) and tin catalyzed ring-opening polymerizations. In order to improve the properties of starch-*graft*-poly(butyl acrylate-*co*-styrene) copolymers, we developed in this contribution a greener process for the dual functionalization of polysaccharide via free-radical graft polymerization and ring-opening functionalization, using phosphoric acid as organocatalyst for the latter, and a one pot one step process in aqueous medium. The new bi-functionalized materials developed herein exhibit remarkable elongations at break, highlighting promising potentialities for stretchable films. The microstructure of copolymers is studied by Nuclear Magnetic Resonance (NMR), Fourier Transform Infrared Spectroscopy (FT-IR), Size Exclusion Chromatography (SEC), Differential Scanning Calorimetry (DSC) and Thermal Gravimetric Analysis (TGA).

84

85 2. Experimental

86

87 The Materials and Characterization procedures are presented in the Appendix A.

88

89 Grafting reactions

90

91 For all reactions, dry starch (30 g) was gelatinized in 120 mL water by heating at 95 °C for 30 minutes. 92 The temperature was then decreased to 85 °C. This leads to the disappearance of the granular structure 93 of starch. The chains are then more accessible for the grafting.

94 - *Free radical grafting*

95 Sodium peroxydisulfate (1 mol % *vs.* starch) previously dissolved in 10 mL of water, butyl acrylate 96 (BA) and/or styrene (St) (70-75 wt % *vs.* starch) were added dropwise for 1 h. The grafting

97 polymerization was carried out for 30 additional minutes. A few experiments carried out under inert
98 atmosphere to avoid oxygen led to similar grafting ratio and microstructures than those conducted under
99 air. The latter experimental conditions were thus chosen for the work.

100 - *Ring-opening grafting*

101 Phosphoric acid (1 mol % vs. ϵ -caprolactone), ϵ -caprolactone (CL) (25 wt % vs. starch) were
102 added dropwise for 1h. The grafting polymerization was carried out for an additional 4 h.

103 - *One pot one step free radical and ring-opening grafting*

104 Sodium peroxydisulfate (1 mol % vs. starch) and phosphoric acid (1 mol % vs. ϵ -caprolactone)
105 previously dissolved in 10 mL of water were added dropwise for 1h via dropping funnel. At the same
106 time, monomers: butyl acrylate and/or styrene (70-75 wt % vs. starch) and ϵ -caprolactone (25-30 wt %
107 vs. starch) were added dropwise for 1 h via second dropping funnel. The grafting polymerization was
108 carried out for an additional 4 h.

109 - *Sequential free radical and ring-opening grafting*

110 Sodium peroxydisulfate (1 mol % vs. starch) previously dissolved in 10 mL of water, butyl
111 acrylate and/or styrene (70-75 wt % vs. starch) were added dropwise for 1 h. The grafting polymerization
112 was carried out for an additional 30 minutes. Then, phosphoric acid (1 mol % vs. ϵ -caprolactone), ϵ -
113 caprolactone (25-30 wt % vs. starch) were then added dropwise for 1h. The grafting polymerization was
114 carried out for an additional 4 h.

115 At the end of the reaction, for each process, the solution was poured in acetone and left during 24 h
116 under magnetic stirring to remove the ungrafted polymer. The product was filtered and dried overnight.
117 The procedure of purification was validated on a few samples by Soxhlet extraction in chloroform during
118 24 h that led to the same ratio.

119

120 The weight grafting percentage (GP) was determined by gravimetry as following:

$$121 \text{ GP} = [(\text{weight copolymer} - \text{weight of starch}) / \text{weight of starch}] \times 100$$
$$122 = [\text{weight of grafted polymer} / \text{weight of starch}] \times 100$$

123

124

125 3. Results and discussion

126

127 3.1. Grafting reaction

128

129 3.1.1 Syntheses of starch-*graft*-poly(butyl acrylate) and starch-*graft*-oligo(ϵ -caprolactone): single
130 starch functionalization

131

132 Entries representative of the grafting reactions starting from butyl acrylate and ϵ -caprolactone
133 on the starch via the different routes are presented in Table 1. Brønsted acid catalysis using phosphoric
134 acid was chosen for the ring-opening since the molecule is harmless at low concentration (it is found in
135 sodas) and it was already used successfully by some of us to graft oligo(ϵ -caprolactone) on dextran and
136 methylated cellulose in aqueous medium (Stanley et al., 2014). Radical and ring-opening
137 functionalizations were first assessed separately. The free radical graft copolymerization of butyl
138 acrylate in water (entry 1) leads to an almost quantitative efficiency, as reported previously (David,
139 2019). Rather long chains are grafted, with a number-average molecular weight of 80 300 g/mol, and a
140 significant dispersity. The resulting degree of substitution (DS) is consequently low, around 0.0014.

141 Regarding the mechanism, the decomposition of potassium persulfate in aqueous medium
142 containing an alcohol is described in the literature (Bartlett & Cotman, 1949). The formation of only
143 $^{\circ}\text{CH}_2\text{OH}$ radicals in methanol has been confirmed by Electron Spin Resonance (Norman, Storey & West,
144 1970). Indeed, radicals are more likely located on the carbon in α position of the oxygen rather

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Table 1 Dual functionalization of starch in aqueous medium: initial assessment ^a

Entry	Route ^b (time)	BA/CL ^c (% wt)	GP ^d (%)	GP _{BA} ^e (%)	GP _{CL} ^e (%)	DS ₁ ^f	DS ₂ ^f	M _n ^g (g/mol)	M _{n corr} ^g (g/mol)	\mathcal{D}_M ^g	T _{g1} ^h (°C)	T _{g2} ^h (°C)	T _{deg 1} ⁱ	T _{deg 2} ⁱ	σ^j (MPa)	ϵ^j (%)
1	Radical (1.5 h)	75/0	69	69	-	0.0014	-	154 000	80 300	6.3	-46	56	254	343	0.3 ± 0.1	1.6±0.4
2	ROP (5 h)	0/25	1.6	-	1.6	0.0223	-	116 ^k	-	-	-	61	-	-	-	-
3	Dual (5 h) <i>Simultaneous</i>	75/25	69	62.5	6.5	0.0953	0.0337	60 800	34 200	3.8	-46	55	250	345	0.9 ± 0.5	2 ± 0.3
4	Dual (1.5 + 5 h) <i>Sequential</i>	75/25	72	68.9	3.1	0.0484	0.0191	44 000	25 500	7.7	-45	59	249	345	0.5 ± 0.1	2 ± 0.5

148

^a The starch was heated at 95 °C for 30 min in water before the grafting reaction at 85 °C.

149 ^b Sodium peroxydisulfate (1 mol % *vs.* starch) and phosphoric acid (1 mol % *vs.* CL) as initiator and catalyst

150 ^c wt % monomer in the feed *vs.* starch

151 ^d Overall grafting percentage determined by gravimetry

152 ^e GP_{PBA} (%) GP_{oligo(CL)} (%) are the grafting percentage of poly(butyl acrylate) and poly(ϵ -caprolactone), respectively, determined by ¹H NMR analysis in DMSO-
153 d₆/CDCl₃ (50/50) (see Appendix B)

154 ^f Degree of substitution, see Appendix A.2. For entries 3 and 4, DS₁ and DS₂ (DS_{PBA} + DS_{PCL}) are determined with the hypothesis of DP_n of 1 and 3, respectively,
155 for oligo(ϵ -caprolactone) because when the grafting was conducted by ROP only, the grafted chains were composed on average of a single caproyl unit.

156 ^g Number-average molecular weight as measured M_n and corrected using Mark-Houwink-Sakurada factors M_{n corr} and dispersity \mathcal{D}_M of the grafted poly(butyl
157 acrylate) chains determined by SEC (40 °C, THF, polystyrene standards) after acid hydrolysis (Appendix A.2)

158 ^h Glass transition temperature (T_g) determined by DSC

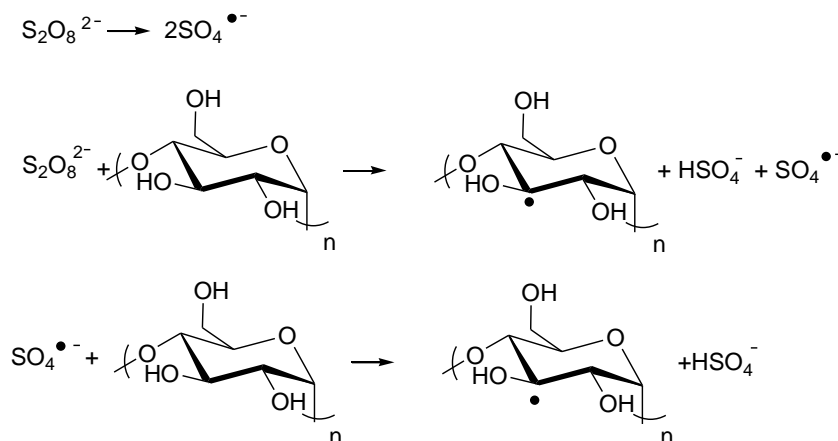
159 ⁱ Temperature of degradation determined by TGA (degradation 1: starch, 2: grafted chains)

160 ^j Maximum stress and elongation at break from tensile strength measurement

161 ^k M_n determined by ¹H NMR analysis in DMSO-d₆ (DP_n = 1.02, see Appendix D)

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164 than on the oxygen, and are more stable on more substituted carbons (Giese, 1986). Thus, it is likely that
 165 the functionalization occurs preferentially on the carbons located on the sugar ring. Considering this, we
 166 propose the initiation mechanism presented in Scheme 1 (the position 3 has been chosen arbitrarily).



182 **Scheme 1.** Proposed radical initiation mechanism in the presence of potassium persulfate in aqueous
 183 medium

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186 The grafting conducted by ring-opening of the cyclic ester leads to a more modest grafting ratio
 187 (entry 2). ^1H NMR analysis shows that the grafted chains are composed on average of a single caproyl
 188 unit (number-average degree of polymerization estimated at 1.02, Appendix D), providing a starch
 189 hydroxyester compound. This result can be explained by the use of water as the solvent of the reaction,
 190 which can either initiate the ROP of ϵ -caprolactone or enable polycondensation via hydroxyacids
 191 resulting from the hydrolysis of the lactone (Scullion & Zinck, 2012), both routes leading to the
 192 formation of oligomers or polymers that are not grafted to the polysaccharide. To improve the yield and
 193 DP, it would have been interesting to use less water or remove it during the reaction but in this case the
 194 viscosity of the medium would be too important. It should be noted that the lactone conversion is
 195 quantitative (^1H NMR analysis given in the Appendix E). The resulting DS is *ca.* 20 times higher than
 196 the one obtained by the radical route, around 0.022 in these experimental conditions.

197 Regarding the grafting mechanism, one can either expect (i) a nucleophilic attack of the
 198 carbohydrate hydroxyl on the lactone catalyzed by phosphoric acid, or (ii) the aforementioned
 199 hydrolysis of the lactone followed by a condensation reaction between the so formed hydroxyacid and
 200 the carbohydrate hydroxyl. This is represented in Scheme 2. Regarding the regioselectivity, we know
 201 from our previous work (Miao et al., 2013) that both primary and secondary carbohydrate hydroxyls can
 202 be engaged in a transesterification reaction with ϵ -caprolactone in the presence of phosphoric acid
 203 moieties. If the pathway (i) is the main mechanism, then we do not expect the reaction to be
 204 regiospecific. For the condensation pathway (ii), primary alcohols are known to be more reactive in
 205 esterification reactions than secondary alcohols. Thus, if this pathway (ii) is the main mechanism, it is
 206 likely that primary alcohols are more involved than secondary alcohols.

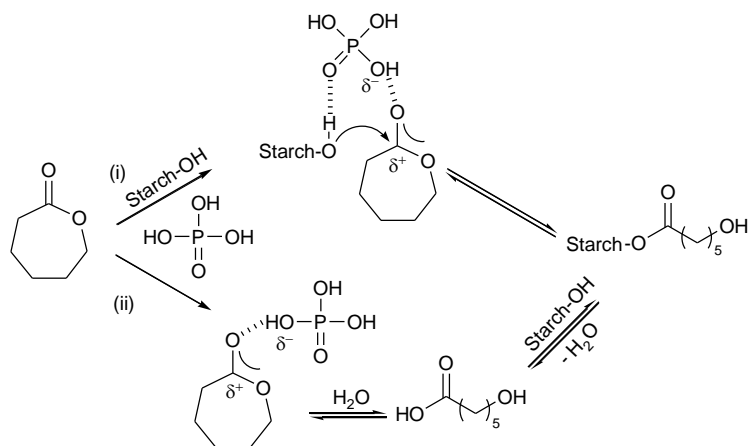
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208 3.1.2 Syntheses of starch-*graft*-[poly(butyl acrylate)/oligo(ϵ -caprolactone)]: dual fonctionnalization

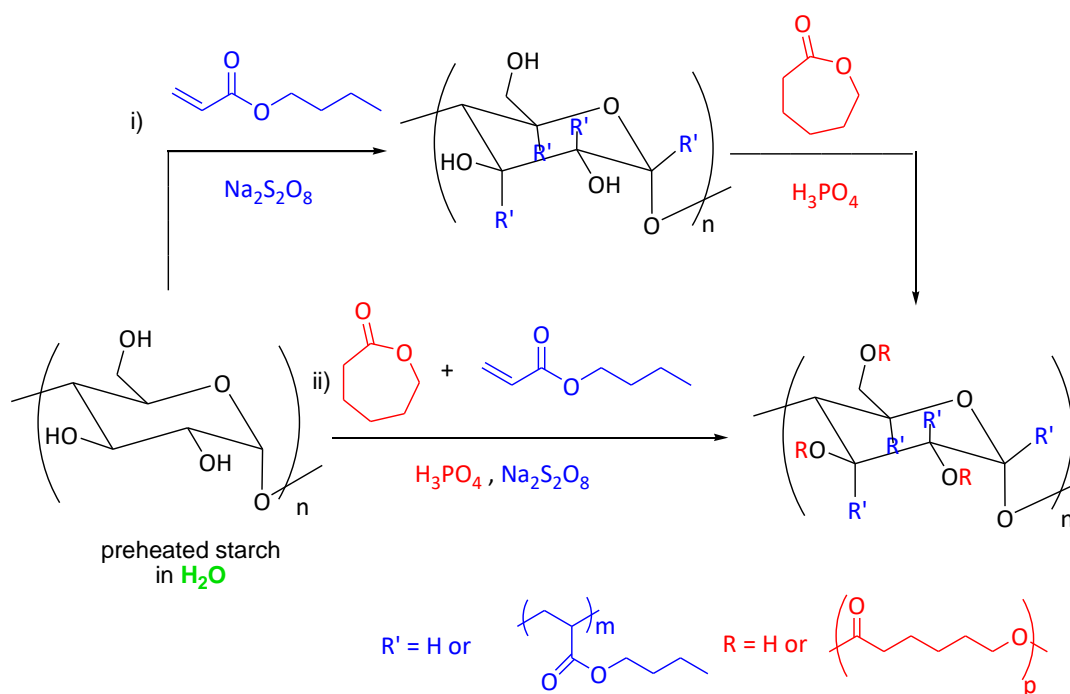
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210 The one pot one step combination of the radical and the ring-opening routes in water
 211 (represented in Scheme 3) is presented entry 3 and the resulting ^1H NMR spectrum is shown Fig.1. The
 212 assignments were made from the ^1H NMR spectra of the starch and of poly(butyl acrylate) that are given
 213 in the Appendix B.

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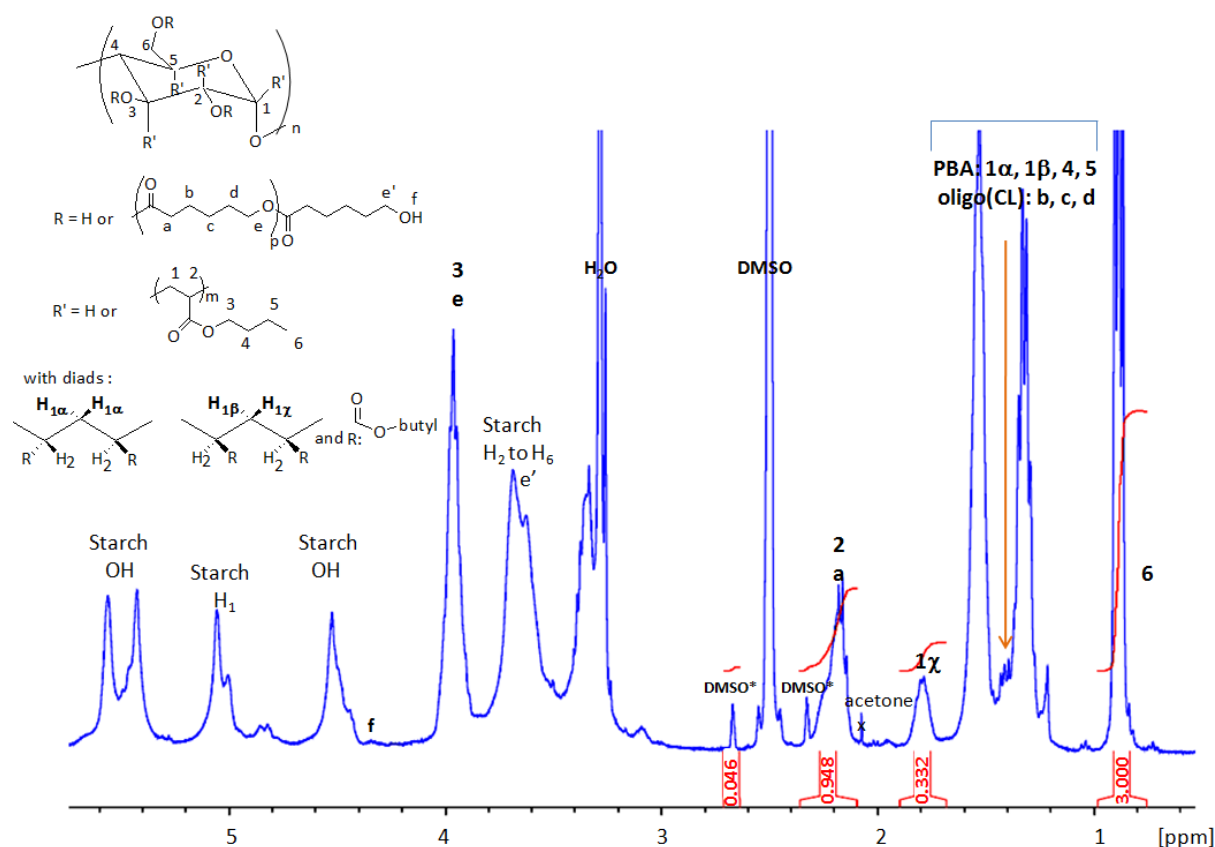


231 **Scheme 2.** Proposed ring-opening mechanism in the presence of ϵ -caprolactone and phosphoric acid in
232 aqueous medium.



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234 **Scheme 3.** One pot one step combined radical and ring-opening route for dual (i: sequential, ii:
235 simultaneous) functionalization of starch in aqueous medium



239 **Fig. 1.** ^1H NMR spectrum of the starch-graft-[poly(butyl acrylate)/oligo(ϵ -caprolactone)] obtained entry
 240 3 in a mixture of $\text{DMSO-}d_6/\text{CDCl}_3$ (50/50, 400 MHz)

241

242 In particular, the $-\text{CH}_2$ signal of the poly(butyl acrylate) backbone is split into three due to the
 243 presence of both *meso* and *racemic* diads (Brar, Kumar & Kaur, 2002). The caproyl and butyl acrylate
 244 signals are overlapping due to the similarity of the molecules, even if a $\text{CH}_2\text{-CH}_2\text{-CH}_2$ caproyl signal
 245 can be evidenced around 1.4 ppm (shown by the arrow in Fig. 1). Signals representative of caproyl units
 246 can also be seen on the ^{13}C NMR spectra of the compounds given in Appendix C. Both butyl acrylate
 247 and ϵ -caprolactone are thus grafted, showing that the two reactions can occur simultaneously in water,
 248 and validating the proof of our concept. If the overall grafting percentage is similar to entry 1, the
 249 grafting ratio of the lactone is significantly improved, by a factor 4. Experiments conducted without the
 250 starch (reported Appendix F) show that this increase of the grafting efficiency may neither be due to a
 251 radical grafting of poly(butyl acrylate) on oligo(ϵ -caprolactone) nor to a transesterification between
 252 acrylate and caproyl units. It may thus be attributed to the hydrophobic character of the PBA grafts
 253 which could lead to an increase in the lactone and/or oligo(ϵ -caprolactone) concentration in the vicinity
 254 of the polysaccharide. The combination of the two chemistries leads to PBA grafts that are significantly
 255 shorter than those obtained by the single radical process. Regarding ϵ -caprolactone, the hydrolyzed
 256 grafts were found to be soluble in the aqueous phase containing the hydrolyzed starch chains and thus
 257 could not be isolated. This is likely due to a very low number-average degree of polymerization, related
 258 to the order of magnitude of 1 found by ^1H NMR for a single ring-opening grafting (entry 2).

259 Experiments combining radical and ring-opening routes were also conducted consecutively, in
 260 a two steps reaction, for the sake of comparison. One can start either by the radical route or by the ring-
 261 opening one. We obtained significant grafting ratios for the consecutive process starting from the free
 262 radical grafting reported entry 4. A slightly higher grafting ratio is obtained, with a lower amount of
 263 cyclic ester, leading to a lower DS. The molecular weight of the graft is in the same order of magnitude,
 264 yet slightly lower. The two steps consecutive reactions starting from ring-opening followed by radical
 265 grafting led to poor results and will not be discussed here.

266 Even if the DS is low, the process can be considered viable as high GP and M_n grafted are obtained
 267 for vinyl grafted. The grafting ratio of oligo(ϵ -caprolactone) is improved by 4 via the combination of
 268 two routes of polymerization in aqueous medium compared to ROP alone.

269

270 3.1.3 Syntheses of starch-*graft*-[poly(butyl acrylate-*co*-styrene)/oligo(ϵ -caprolactone)]

271 The combination of radical and ring-opening grafting was then realized using styrene as a
 272 comonomer with butyl acrylate for the radical polymerization. The insertion of styrene into poly(butyl
 273 acrylate) is expected to have an impact on the properties of the resulting materials, by *e.g.* modulating
 274 the thermal and mechanical properties. Representative results are given entries 6 and 9 in Table 2
 275 together with the reactions conducted in the sequential way (7 and 10) and via the single radical route
 276 (5 and 8) for comparison.

277

278 **Table 2.** Dual functionalization of starch in aqueous medium with styrene and butyl acrylate as vinyl
 279 comonomers^a

Entry	Route (time) ^b	BA/St/CL ^c (%wt)	GP ^d (%)	BA/St ^d (%)	M_n^e (g/mol)	\mathcal{D}_M^e	T_{g1}^f (°C)	T_{g2}^f (°C)	$T_{deg\ 1}^g$	$T_{deg\ 2}^g$
5	Radical (1.5 h)	50/25/0	64	62/38	91 300	4.4	4	59	250	356
6	Dual (5 h) <i>Simultaneous</i>	50/25/25	71	67/33	63 200	2.5	-1	56	252	351
7	Dual (1.5 + 5 h) <i>Sequential</i>	50/25/25	72	68/32	71 000	2.9	0	56	245	352
8	Radical (1.5 h)	35/35/0	65	47/53	85 900	2.8	20	57	253	357
9	Dual (5 h) <i>Simultaneous</i>	35/35/30	65	49/51	63 500	2.3	18	58	248	359
10	Dual (1.5 + 5 h) <i>Sequential</i>	35/35/30	75	48/52	59 000	2.8	18	58	249	359

280

281 ^a The starch is heated at 95 °C for 30 min in water before the grafting reaction at 85 °C.

282 ^b Sodium peroxydisulfate (1 mol % *vs.* starch) and phosphoric acid (1 mol % *vs.* CL) as initiator and
 283 catalyst

284 ^c wt % monomer in the feed *vs.* starch

285 ^d Overall grafting percentage determined by gravimetry, ratio of BA/St units in grafted chains was
 286 determined by ¹H NMR analysis in DMSO-*d*₆/CDCl₃ (50/50) (Appendix G)

287 ^e Number-average molecular weight M_n and dispersity \mathcal{D}_M of the grafted poly(butyl acrylate-*co*-styrene)
 288 chains determined by SEC (40 °C, THF, polystyrene standards) after acid hydrolysis (Appendix A.2)

289 ^f Glass transition temperature determined by DSC

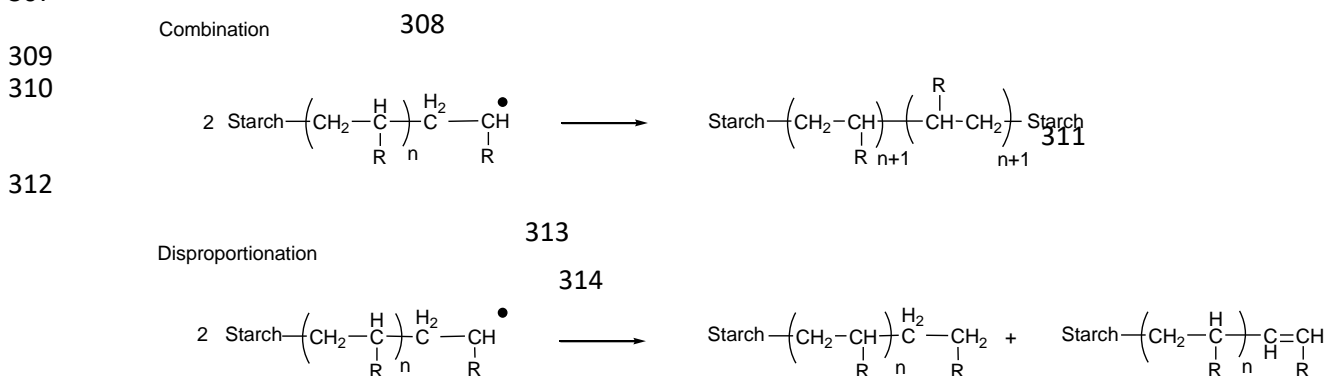
290 ^g Temperature of degradation determined by TGA (degradation 1: starch, 2: grafted chains)

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292

293 The resulting grafting percentage is in the same order of magnitude than the one obtained using
 294 only butyl acrylate in similar conditions (*e.g.* entries 5-6-7 *vs.* 1-3-4). The determination of the individual
 295 grafting ratio, *i.e.* poly(butyl acrylate-*co*-styrene) *vs.* oligo(ϵ -caprolactone) is not possible by the ¹H
 296 NMR method used previously due to signal overlapping, and we did not find any other suitable method
 297 despite several trials. However, the ratio of butyl acrylate *vs.* styrene units in the grafted chains could
 298 be determined by ¹H NMR analysis as reported in the Appendix G. It can be seen that the composition
 299 of the poly(butyl acrylate-*co*-styrene) grafts follows the monomer feed. The molecular weights follow
 300 the same trends as those observed while grafting PBA, *i.e.* M_n values lower than those obtained from the
 301 radical process alone, the difference between the two processes being less important in the presence of
 302 styrene. This could be explained by radical chains scissions. It is indeed known that acrylates favor the

303 occurrence of termination reaction by disproportionation while termination by combination is the main
 304 process with styrene as the monomer (see Scheme 4) (Nakamura & Yamago, 2015). This may also
 305 explain that the dispersities observed in the presence of the three monomers are lower than those
 306 observed in the absence of styrene (2.5-4.4 vs. 3.8-7.7).
 307



318 **Scheme 4.** Termination reactions by combination and disproportionation
 319
 320

321 The copolymers were analyzed by FT-IR (spectra in the Appendix H). The presence of the bands
 322 at 1730 cm⁻¹ (ν(C=O)), at 1250 cm⁻¹ (ν(C-O)), and at 700 cm⁻¹ (deformation of aromatic function) are
 323 characteristic of the butyl acrylate, caproyl and styrene groups respectively. The stretching frequencies
 324 for ν_{as}(CH₃) and ν_s(CH₃) (corresponding to methyl of butyl chain) are observed at 2960 and 2872 cm⁻¹,
 325 respectively.
 326

327 3.2 Thermal analyses

328
 329
 330 DSC analyses carried out on the grafted copolymers at 50 % relative humidity (thermograms in
 331 the Appendix I) reveal two glass transition temperatures (T_g) for all samples involving the radical
 332 process, that are given in Table 1 and Table 2. The T_g at -46 °C observed for entries 1; 3-4 corresponds
 333 to the T_g of poly(butyl acrylate). The second T_g is found around 55 to 59 °C for all samples, whatever
 334 the composition of the grafts, and is attributed to the glass transition of the starch backbone. The starch
 335 alone has indeed a T_g around 60 °C in similar conditions. When styrene is used as a comonomer for the
 336 radical process, the low T_g found around 2 °C (entries 5-7) and 19 °C (entries 8-10) increases with
 337 increasing amount of styrene, the T_g of polystyrene being around 100 °C. The presence of a single T_g
 338 for poly(butyl acrylate-*co*-styrene) grafted chains confirms a statistical microstructure which can be
 339 expected from the reactivity ratios of the two monomers, r_{St} 0.73-0.87 and r_{BA} 0.17-0.30 (Fernández-
 340 García et al., 2000). The thermograms did not show oligo(ε-caprolactone) glass transition or melting
 341 temperatures, which can be ascribed to the low grafting ratio and the short size of the grafts. The
 342 observation of two T_g by DSC is an indication of a phase separation between starch and the grafted
 343 polymer, which was already observed by us on starch-*graft*-poly(butyl acrylate) and starch-*graft*-
 344 polystyrene copolymers in the form of two co-continuous phases (transmission electron microscopy
 345 analyses, David et al., 2019).
 346

347 TGA analyses were performed on the graft copolymers (Tables 1 and 2, curves in the Appendix
 348 J). On all products, evaporation of water (contained in starch) below 100°C is observed. The unmodified
 349 starch substrate degrades from 250 °C. Two main degradation stages are observed on the copolymers:
 350 degradation of the starch part from 250 °C and degradation of grafted chains from 340 °C (entries 1-4)
 351 or 350°C (entries 5-10). Adding styrene units on the copolymer increases the stability of the grafting
 chains. The short grafts of oligo(ε-caprolactone) may degrade on the same stage as that of starch. Indeed,

352 for example starch acetates degrade in one stage of decomposition, the degradation being shifted towards
353 higher temperatures with increasing DS (Wang et al., 2008).

354

355

356 3.3 Mechanical behaviour

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358 Mechanical tests were then performed at 50 % relative humidity and room temperature. The
359 results are presented in Table 1 (entries 1-4) and Figure 2A (entries 5-10). The temperature at which the
360 mechanical tests were conducted is thus above the T_g of the grafted chains, which are as a consequence
361 at the rubbery state, except for entries 8-10 where the T_g of the grafted chains is around 20 °C, and below
362 the T_g of the starch. The copolymers obtained via single free-radical grafting copolymerization exhibit
363 modest mechanical properties, with a stress at break around 0.3 MPa and an elongation at break close
364 to 1.6 % (entry 1). The replacement of one third butyl acrylate by styrene in the feed allows to increase
365 these properties to 8.7 MPa and 4.4 %, respectively, for the starch-*graft*-poly(acrylate-*co*-styrene)
366 copolymer of entry 5. If the combination of the radical and ring-opening routes has a modest effect when
367 butyl acrylate is used as a single radical monomer (entries 3 *vs.* 1), it leads to an impressive increase of
368 the elongation at break when performed in the presence of 25% styrene (entries 6 *vs.* 5), by a factor as
369 high as 17. When the radical grafting is performed with an equimolar amount of styrene and acrylate,
370 the combination of the processes leads in turn to an increase of the stress at break from 6.6 to 7.4 MPa
371 (entries 9 *vs.* 8), with a smooth increase of the elongation at break. The sequential route leads to similar
372 results, with however a lower elongation at break (entry 7 *vs.* 6).

373 Both routes lead to similar performances in terms of GP, Mn, and thermal properties. The
374 simultaneous route leads in turn to higher elongation at break. The promising results obtained in entry
375 6 (BA/St/CL 50/25/25, $\epsilon = 75$ %) prompted us to go further in this direction.

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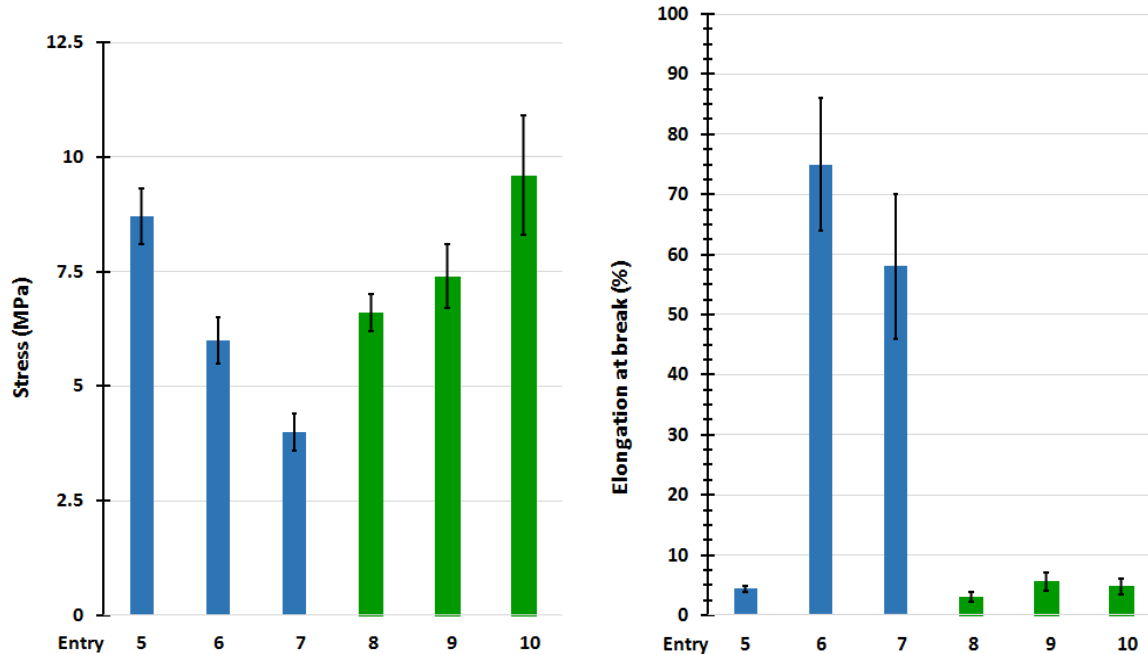
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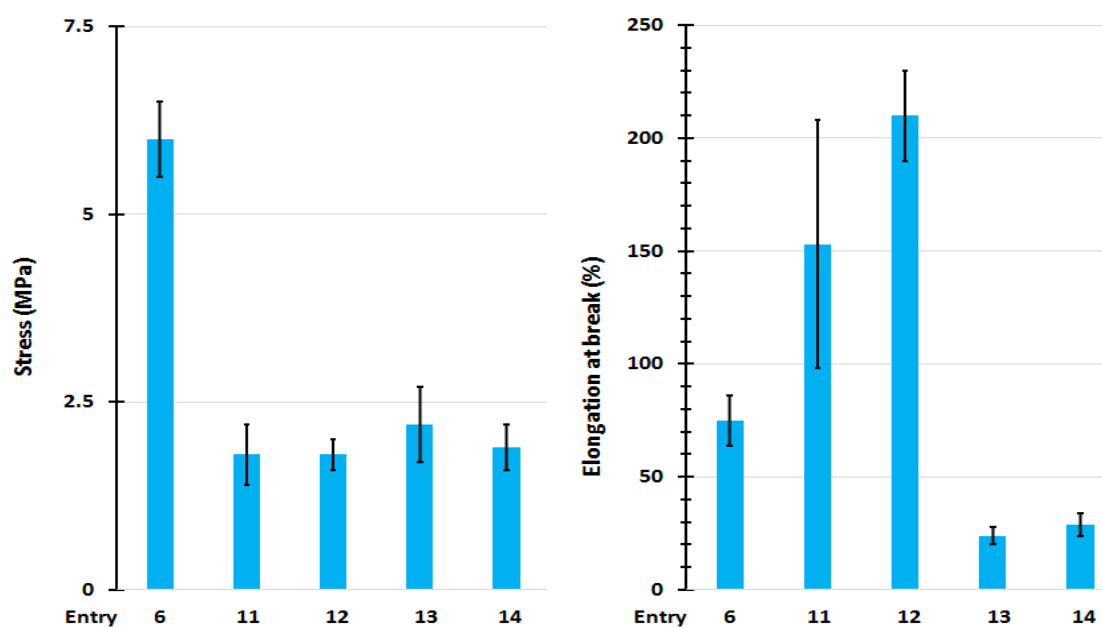
A : Copolymers Entries 5-10 (Table 2)



**5 : Radical (50%BA / 25%St)
(35%BA / 35%St)**

8 : Radical

B : Copolymers Entries 6, 11-14 (Table 3)



6 : 50%BA / 25%St / 25% CL

Dual Simultaneous

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Fig 2 Stress and elongation at break of starch-graft-[poly(butyl acrylate-co-styrene) / oligo(ϵ -caprolactone)] at 20 °C, 50 % RH (numerical values Appendix K) in function of the monomers ratio (wt% vs. starch).

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3.5 Final adjustment of feed ratio: optimization of mechanical behaviour

A fine modification of the feed was realized in order to assess the effect of the composition on the mechanical properties in this range. The results are reported in Table 3 and Fig. 2B (the mechanical curves are presented in the Appendix K).

400 **Table 3** Simultaneous dual functionalization of starch in aqueous medium: optimization of the
401 elongation at break^a

Entry	BA/St/CL ^b (% wt)	GP ^c (%)	M _n ^d (g/mol)	Đ _M ^d	T _{g1} ^e (°C)	T _{g2} ^e (°C)
6	50/25/25	71	63 200	2.5	-1	56
11	50/20/30	69	62 000	2.8	-5	60
12	55/20/25	72	64 000	3.0	-10	59
13	55/15/30	68	66 000	2.6	-17	53
14	60/15/25	73	63 000	3.0	-21	57

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^a The starch is heated at 95 °C for 30 min in water before the grafting reaction at 85 °C for 5 h. Sodium peroxydisulfate (1 mol % vs. starch) and phosphoric acid (1 mol % vs. CL) as initiator and catalyst.

^b wt % monomer in the feed vs. starch

^c Overall grafting percentage determined by gravimetry

^d Number-average molecular weight M_n and dispersity Đ_M of the grafted poly(butyl acrylate-*co*-styrene) chains determined by SEC (40°C, THF, polystyrene standards) after acid hydrolysis (Appendix A.2)

^e Glass transition temperature determined by DSC

411 The fine variation of the monomer ratios has neither a substantial influence on the grafting
412 percentages (68-73 %), nor on the molecular weight distributions of the polyvinyl grafts (*M* values 62
413 000 to 66 000 g/mol and dispersities 2.6 to 3). The T_g of the grafted chains was found to be below 0 °C
414 whatever the ratios. Mechanicals tests performed on these materials reveals elongations at break from
415 *ca.* 20 % up to 207 % in this composition range (Fig. 2B.) The composition yielding to the higher
416 elongation (BA/St 55/20) was assessed without the lactone, leading to a value of 14%. An increase factor
417 of *ca.* 15 is thus confirmed while combining the two grafting processes for making the dual
418 functionalized material. It is worth noting that the grafting of a small quantity of oligo(ε-caprolactone)
419 allows to access to thermoplastic resins with interesting mechanical properties.

420 The visual observation of the specimen during the tensile test reported in Fig. 3 may bring some
421 explanations of the phenomenon. Among the hypotheses able to explain the drop of elongation observed,
422 a necking process during uniaxial tensile tests is clearly disregarded since there is no significant
423 reduction in the section of the specimen located during the deformation. It can be seen that the specimens
424 with high deformations whiten during tensile test. This bleaching is even more noticeable as the film is
425 transparent before the test. It could be ascribed to the formation of cavities. In fact, cavitation is
426 manifested by an increase in the inelastic volume and by a modification of the optical properties of the
427 material (bleaching). The deformation profile, where a decrease in the maximum stress during the plastic
428 deformation is observed, is also in agreement with cavitation phenomenons. The elongation at which
429 the fracture occurs depends on the distribution of these cavities, *i.e* localized or in the whole material,
430 and on the number of these cavities. The volume of deformation increases because of the creation of
431 micro-voids while the shear operates without volume variation (Mikus et al., 2014). A more deep study
432 is however necessary to confirm this hypothesis, and will be the subject of a forthcoming paper.

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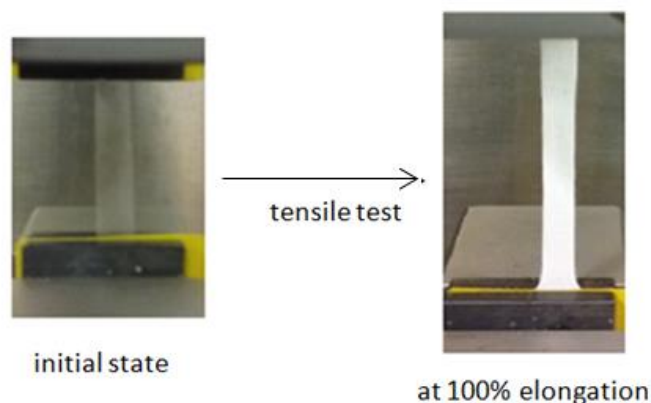
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447 **Fig. 3.** Evolution of the specimen during mechanical test of the starch-*graft*[poly (butyl acrylate-*co*-
448 styrene acrylate) / oligo (ϵ -caprolactone)] (55% BA / 20% St / 25% CL) obtained by "Radical + ROP"
449 process
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451 4. Conclusions

452 The dual functionalization of a starch is reported in a one pot one step route in aqueous medium,
453 by combining free radical and ring-opening chemistries. Starch-*graft*-[poly(butyl acrylate)/oligo(ϵ -
454 caprolactone)] and starch-*graft*-[poly(butyl acrylate-*co*-styrene)/oligo(ϵ -caprolactone)] copolymers
455 were synthesized using sodium peroxydisulfate as radical initiator and phosphoric acid as
456 organocatalyst. Compared to the single ring-opening process, an improvement in the grafting percentage
457 of oligo(ϵ -caprolactone) is observed, by a factor of 2 to 4. The DSC analysis showed the presence of
458 two glass transition temperatures, one related to the starch part and the other to the grafted vinyl
459 polymers and being dependent on the butyl acrylate / styrene ratio. Interestingly, the resulting dual
460 functionalized starches shows elongations at break as high as 210 % (BA/St/CL 55/20/25), a 15 fold
461 increase when compared to the single free radical functionalization. The materials show thus promising
462 potentialities in the field of stretchable films for light occulting applications.

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464 CRediT authorship contribution statement

465 Julie Meimoun: Conceptualization, Investigation, Methodology, Validation, Writing - original
466 draft. Vincent Wiatz: Supervision, Validation. René Saint-Loup: Supervision, Validation, Writing –
467 review. Julien Parcq: Supervision, Validation. Adéline David: Methodology. Grégory Stoclet:
468 Methodology. Valérie Gaucher: Methodology. Audrey Favrelle-Huret: Conceptualization, Supervision,
469 Validation, Writing – review. Fanny Bonnet: Conceptualization, Supervision, Validation, Writing –
470 review. Philippe Zinck: Conceptualization, Methodology, Supervision, Validation, Writing - original
471 draft, Writing – review.

472

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480 **References**

481

482 Aburto, J., Alric, I., & Borredon, E. (1999). Preparation of Long-chain Esters of Starch Using Fatty Acid
483 Chlorides in the Absence of an Organic Solvent. *Starch/Stärke*, *51*, 132–135.

484

485 Avérous, L., & Halley, P. J. (2009). Biocomposites based on plasticized starch. *Biofuels, Bioproducts*
486 *and Biorefining*, *3*(3), 329–343.

487

488 Bartlett, P. D., & Cotman, J. D. (1949). The Kinetics of the Decomposition of Potassium Persulfate in
489 Aqueous Solutions of Methanol. *Journal of the American Chemical Society*, *71*, 1419–1422.

490

491 Berthier, D. L., Herrmann A., & Ouali, L. (2011). Synthesis of hydroxypropyl cellulose derivatives
492 modified with amphiphilic diblock copolymer side-chains for the slow release of volatile molecules.
493 *Polymer Chemistry*, *2*, 2093–2101.

494

495 Brar, A. S., Kumar, R., & Kaur, M. (2002). Poly(methyl acrylate): Spectral Assignment by Two-
496 Dimensional NMR Spectroscopy. *Applied Spectroscopy*, *56*, 1380–1382.

497

498 Cazotti, J. C., Fritz, A. T., Garcia-Valdez, O., Smeets, N. M. B., Dubé, M. A., & Cunningham, M. F.
499 (2020). Graft modification of starch nanoparticles using nitroxide-mediated polymerization and the
500 grafting from approach. *Carbohydrate Polymers*, *228*, 115384–115393.

501

502 Chang, F., Yamabuki, K., Onimura, K., & Oishi, T. (2008). Modification of Cellulose by Using Atom
503 Transfer Radical Polymerization and Ring-Opening Polymerization. *Polymer Journal*, *40*, 1170–1179.

504

505 Chen, J., Kamitakahara, H., & Edgar, K. J. (2020). Synthesis of polysaccharide-based block copolymers
506 via olefin crossmetathesis. *Carbohydrate Polymers*, *228*, 115530–115540.

507

508 Chen, L., Ni, Y., Bian, X., Qiu, X., Zhuang, X., Chen, X., & Jing, X. (2005) A novel approach to grafting
509 polymerization of ϵ -caprolactone onto starch granules. *Carbohydrate Polymers*, *60*, 103–109.

510

511 Chen, Q., Yu, H., Wang, L., Abdin, Z., Chen, Y., Wang, J., Zhou, W., Yang, R., Khan, R., Zhang, H.,
512 & Chen, X. (2015). Recent progress in chemical modification of starch and its applications. *RSC*
513 *Advances*, *5*, 67459–67474.

514

515 Choi, E.-J., Kim, C.-H., & Park, J.-K. (1999). Synthesis and Characterization of Starch-g-
516 Polycaprolactone Copolymer. *Macromolecules*, *32*, 7402–7408.

517

518 David, A., Meimoun, J., Delaunay, T., Wiatz, V., Saint-Loup, R., Parcq, J., Descamps, N., Favrelle, A.,
519 Bonnet, F., Stoclet, G., Lourdin, D., Zinck, P., & Gaucher, V. (2019). Structural characterization and
520 mechanical properties of dextrin-graft-poly(butyl acrylate-co-styrene) copolymers. *Express Polymer*
521 *Letters*, *13*, 235–247.

522

523

524 Fan, Y., & Picchioni, F. (2020). Modification of starch: A review on the application of “green” solvents
525 and controlled functionalization. *Carbohydrate Polymers*, *241*, 116350–116369.

526

527 Fernandez-Garcia, M., Fernandez-Sanz, M., Madruga, E. L., Cuervo-Rodríguez, R., Hernández-Gordo,
528 V., & Fernández-Monreal, M. C. (2000). Solvent effects on the free-radical copolymerization of styrene
529 with butyl acrylate. I. Monomer reactivity ratios. *Journal of Polymer Science: Polymer Chemistry*, *38*,
530 60–67.

531

532 Giese, B. (1986). Radicals in Organic Synthesis: Formation of Carbon-Carbon Bonds. *Organic*
533 *Chemistry Series*, Pergamon Press, 5.

534

535 Haq, F., Yu, H., Wang, L., Liu, J., Mehmood, S., Haroon, M., Amin, B., Fahad, S., & Uddin, M. A.
536 (2020). Dual modification of starches by phosphorylation and grafting and their application as
537 adsorbents for the removal of phenol. *Journal of Polymer Research*, 27, 313–324.
538

539 Imre, B., García, L., Puglia, D., & Vilaplana, F. (2019). Reactive compatibilization of plant
540 polysaccharides and biobased polymers: Review on current strategies, expectations and reality.
541 *Carbohydrate Polymers*, 209, 20–37.
542

543 Jyothi, A. N. (2010). Starch Graft Copolymers: Novel Applications in Industry. *Composite Interfaces*,
544 17, 165–174.
545

546 Liu, Y., Huang, G., Pang, Y., Han, M., & Ji, S. (2015). One-Pot Synthesis of Thermoresponsive
547 Cellulose-Based Miktoarm Graft Copolymer by Simultaneous ATRP and ROP. *Journal of Renewable*
548 *Materials*, 3, 113–119.
549

550 Lourdin, D., Coignard, L., Bizot, H., & Colonna, P. (1997). Influence of equilibrium relative humidity
551 and plasticizer concentration on the water content and glass transition of starch materials. *Polymer*, 38,
552 5401–5406.
553

554

555 Meimoun, J., Wiatz, V., Saint-Loup, R., Parcq, J., Favrelle, A., Bonnet, F., & Zinck, P. (2018).
556 Modification of starch by graft copolymerization. *Starch/Stärke*, 70, 1600351-1600374.
557

558 Meshram, M. W., Patil, V. V., Mhaske, S. T., & Thorat, B. N. (2009). Graft copolymers of starch and
559 its application in textiles. *Carbohydrate Polymers*, 75, 71–78.
560

561 Miao, Y., Phuphuak, Y., Rousseau, C., Bousquet, T., Mortreux, A., Chirachanchai, S., & Zinck, P.
562 (2013). Ring-opening polymerization of lactones using binaphthyl-diyl hydrogen phosphate as
563 organocatalyst and resulting monosaccharide functionalization of polylactones. *Journal of Polymer*
564 *Science Part A: Polymer Chemistry*, 51, 2279–2287.
565

566 Mikus, P.-Y., Alix, S., Soulestin, J., Lacrampe, M. F., Krawczak, P., Coqueret, X., & Dole, P. (2014).
567 Deformation mechanisms of plasticized starch materials. *Carbohydrate Polymers*, 114, 450–457.
568

569 Mou, J., Li, X., Wang, H., Fei, G., & Liu, Q. (2012). Preparation, characterization, and water resistance
570 of cationic acetylated starch-g-poly(styrene-butyl acrylate) surfactant-free emulsion. *Starch/Stärke*, 64,
571 826–834.
572

573

574 Nakamura, Y., & Yamago, S. (2015). Termination Mechanism in the Radical Polymerization of Methyl
575 Methacrylate and Styrene Determined by the Reaction of Structurally Well-Defined Polymer End
576 Radicals. *Macromolecules*, 48, 6450–6456.
577

578 Norman, R. O. C., Storey, P. M., & West, P. R. (1970). Electron Spin Resonance Studies. Part XXV2
579 Reactions of the Sulphate Radical Anion with Organic Compounds. *Journal of the Chemistry Society*
580 *B: Physical Organic*, 1087–1095.
581

582 Östmark, E., Nyström, D., & Malmström, E. (2008). Unimolecular Nanocontainers Prepared by ROP
583 and Subsequent ATRP from Hydroxypropylcellulose. *Macromolecules*, 41, 4405–4415.
584

585 Rutot-Houzé, D., Degée, P., Gouttebaron, R., Hecq, M., Narayan, R., & Dubois, P. (2004). In-depth
586 characterization of granular starch-graft-polyester compositions as obtained by *in situ* polymerization
587 of lactones from the starch surface. *Polymer International*, 53, 656–663.
588

589 Scullion, R., & Zinck, P. (2012). Precipitation polymerization of ε-caprolactone in water using metal
590 triflates as catalysts. *Polymer Bulletin*, 69, 757–763.
591

- 592 Shogren, R. L. (2003). Rapid preparation of starch esters by high temperature/pressure reaction.
593 *Carbohydrate Polymers*, 52, 319–326.
594
- 595 Stanley, N., Bucataru, G., Miao, Y., Favrelle, A., Bria, M., Stoffelbach, F., Woisel, P., & Zinck, P.
596 (2014). Brønsted Acid-Catalyzed Polymerization of ε-Caprolactone in Water: A Mild and
597 Straightforward Route to Poly(ε-caprolactone)-graft-Water-Soluble Polysaccharides. *Journal of*
598 *Polymer Science Part Polymer Chemistry*, 52, 2139–2145.
599
- 600 Vlček, P., Janata, M., Látalová, P., Dybal, J., Špírková, M., & Toman, L. (2008). Bottlebrush-shaped
601 copolymers with cellulose diacetate backbone by a combination of ring opening polymerization and
602 ATRP. *Journal of Polymer Science Part A: Polymer Chemistry*, 46, 564–573.
603
- 604 Wang, X., Gao, W., Zhang, L., Xiao, P., Yao, L., Liu, Y., Li, K., & Xie, W. (2008). Study on the
605 morphology, crystalline structure and thermal properties of yam starch acetates with different degrees
606 of substitution. *Science in China Series B: Chemistry*, 51, 859–865.
607
- 608 Wang, X. L., Yang, K. K., & Wang, Y. Z. (2003). Properties of starch blends with biodegradable
609 polymers. *Journal of Macromolecular Science*, 43, 385–409.
610
- 611 Xiaofei, M., Jiugao, Y., & Jin, F. (2004). Urea and formamide as a mixed plasticizer for thermoplastic
612 starch. *Polymer International*, 53, 1780–1785.
613
- 614 Yan, Q., Yuan, J., Zhang, F., Sui, X., Xie, X., Yin, Y., Wang, S., & Wei, Y. (2009). Cellulose-Based
615 Dual Graft Molecular Brushes as Potential Drug Nanocarriers: Stimulus-Responsive Micelles, Self-
616 Assembled Phase Transition Behavior, and Tunable Crystalline Morphologies. *Biomacromolecules*, 10,
617 2033–2042.